Center for Convergence and
Emerging Networking Technologies

Competitive Evaluation of Three-stream 802.11n Access Points

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Executive Summary

In many enterprises, wired connectivity is no longer the default— or even the primary— mode of network access. With the escalating number of wireless devices and the accompanying demand for increased bandwidth, Wi-Fi-serving enterprises must ensure that end-users have a consistent experience. The state of the art in Wi-Fi technology is dual-band, three-stream 802.11n access points, devices which are marketed by their vendors with exceptionally high data rates. These metrics, while not altogether untrue, account only for maximum physical layer data rates; achievable application layer throughput is typically lower and often more than halved, even under optimal conditions. Throughput is hampered not only by layer 2 retransmissions and dozens of clients, but by the vast amount of overhead associated with 802.11 protocols.

The Center for Convergence and Emerging Networking Technologies, housed in the School of Information Studies at Syracuse University, partnered with Ruckus Wireless to determine the level of throughput network administrators could expect from five leading vendors' indoor three-stream access points in an environment that resembles real-world deployments. Our tests are an attempt to discover what the top aggregate throughput for each vendor's access point might be, as well as how each product scales under the load of many clients and an increasingly difficult RF environment. Vendors included Aerohive Networks, Aruba Networks, Cisco Systems, Meraki, and Ruckus Wireless. We performed a battery of tests in three broad categories:

- Single AP, single client (rate v. range)
- Multiple classrooms of simultaneous users (90) on a single AP
- Multiple classrooms of simultaneous users (120) using multiple APs (6)

To be clear, our evaluation of vendors' products was not a comprehensive product review. We did not compare total cost of ownership, ease of management, or advanced features and functionality, all of which may be more important than raw throughput in some environments. In addition, since our primary interest involved the assessment of maximum system throughput, we conducted all our testing with three-stream client devices. While we made a diligent effort to optimize each product for maximum performance, we do not disclaim the possibility that each vendor's product could have been configured in a more optimal manner. New software releases might also result in better performance.

While all of the products we tested provided throughput levels that will meet the needs of most organizations, we found significant variation in their performances. Our results suggest that Ruckus Wireless' ZoneFlex 7982 offers the best overall performance of any of the products we tested. In addition, we found Ruckus' performance to be significantly more consistent as we altered key elements of the physical environment.

Test Objectives

The IEEE 802.11n-2009 standard describes the maximum data rate for three-stream products as 450 Mbps per band, 150 Mbps per stream. Put another way, a WLAN vendor selling simultaneous dual-band three-stream access points could claim a speed of 900 Mbps for their products (2 x 450). It is no lie for vendors to publish the 900 Mbps figure, as it is, in theory, possible to reach. Often forgotten in the excitement over such a high rate, though, are two important factors:

1. Data rate is not the same thing as throughput, and throughput will never measure up to the data rate. *Data rate* is the speed of the transmission, "the number of bits per second the Physical layer carries during a single-frame transmission"[1]. *Throughput* is the effective transmission rate experienced by applications[2]. The difference between the data rate and throughput can be explained by 802.11 protocol overhead, including contention mechanisms, frame acknowledgements, and management packets, as well as by the quality of physical layer signal levels, which impact the data rates associated with a client's connection to an AP.

2. The technical requirements by which practitioners can reach 450 Mbps in each band are often untenable in an enterprise environment. 40 MHz channel widths, essential to reaching maximum rates, use two of the three non-overlapping channels at the 2.4 GHz band, making channel reuse— essential to capacity-oriented network designs— very difficult. This constraint effectively limits maximum aggregate throughput in a simultaneous dual-band environment to 216.7 Mbps in 2.4 GHz and 450 at 5 GHz[3], a total data rate of 666.7 Mbps— markedly less than 900 Mbps.

The Center for Convergence and Emerging Networking Technologies, in a partnership with Ruckus Wireless[4], evaluated 802.11n three-stream access points, focused on performance, specifically aggregate TCP throughput. Wired connectivity, once the default access mode, is no longer even the primary path to the network, yet wireless performance must be as consistent and reliable as using a cable has been. Our hope is that implementers can use these results in planning for capacity-based WLANs, and that WLAN vendors can use our findings to enhance their performance relative to their competitors.

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[1] Coleman, D., & Westcott, D. (2012). *CWNA: Certified Wireless Network Administrator Official Study Guide Exam PW0-105.* (3rd ed., pg 157). Indianapolis, IN: John Wiley.

[2] 802.11 is a layer 1 and 2 protocol. While a user may truly only care for her layer 7 traffic, overhead in a WLAN is all traffic that is not layer 3 - 7.

[3] http://en.wikipedia.org/wiki/IEEE_802.11n-2009#Data_rates

[4] Ruckus Wireless, of Sunnyvale, CA, is one of several WLAN vendors with whom the School of Information Studies has a close working relationship. Ruckus provided the equipment for the tests in this paper and also funded a grant at the iSchool to improve the state of Wi-Fi education.

Test Configuration, Tools, and Methodology

We tested the following access points:

- Aerohive: **AP330**, controlled by HiveManager Online[5]
- Aruba Networks: **AP-135**, with the Aruba 3200 controller[6]
- Cisco: **3602i**, with the 5500 WLAN controller[7]
- Meraki: **MR24**, controlled by Enterprise Cloud Controller[8]
- Ruckus Wireless: **ZoneFlex 7982**, with the ZoneDirector 3000[9]

We used only three-stream capable client devices in our tests. Our laptop clients were early 2011 MacBook Pros[10] with several of Dell's Latitude E5520's[11]. In our multi-client tests, we leveraged the availability of 90 PCs[12] in computer labs and bestowed wireless connectivity via two brands of three-stream USB adapters, Netgear WNDA4100 and Linksys AE3000[13]. We recognize that many enterprise networks may not sport all three-stream-capable devices. While we believe Wi-Fi will trend towards MIMO devices of increasing streams, we were interested in designing our tests so that we could measure the maximum aggregate throughput of our vendors' access points.

Testing took place on the ground floor of Hinds Hall, home of the School of Information Studies at Syracuse University, Syracuse, NY. Hinds Hall has features typical of a higher education environment: carpeted classrooms, glass-windowed computer laboratories, tiled floors, and steel HVAC ceiling runs. Tests were performed at night, between 11PM and 6AM. The University runs its own wireless network, which was brought down in Hinds Hall during the test window. Before test runs began, we used Metageek's Chanalyzer Pro spectrum analyzer, to sweep through the ground floor to ensure the environment was quiet as expected.

While we believe our findings are representative of what others can expect, it is important to understand that RF behaves differently in different environments. A bit-for-bit replication is unlikely even within Hinds Hall, much less a dissimilar location. However, we stand by our data because they are borne out of repeated and carefully instrumented tests.

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[5] Aerohive HiveManager Online: *Test 1*: 5.0r3. *Tests 2 and 3*: 5.1r1

[6] Aruba 3200: *Tests 1 and 2*: 6.1.3.2. Test 3: 6.1.3.4

[7] Cisco 5500: 7.2.110.0

[8] Meraki does not publish version numbers for their Enterprise Cloud Controller.

[9] Ruckus ZoneDirector 3000: 9.4.0.0 (build 110)

[10] MacBookPro 8,1. Broadcom BCM4331 chipset, running OS X 10.7.4

[11] Intel Centrino Ultimate-N 6300. 15.1.1.1 driver, running Windows 7 SP1

[12] 60 Dell Optiplex 790's, and 30 Dell Optiplex 960's

[13] Both adaptors are based on the Ralink RT3573 reference design. The Netgear devices were running version 1.2.0.0 of its firmware, while the Linksys adaptors all had version 3.2.8.0 of its firmware installed.

Test Software

Ixia's IxChariot was used across all tests to evaluate throughput. IxChariot Console[14] runs on a Windows computer[15], serving tests to clients which have software agents installed. These agents, branded "Performance Endpoints", are instructed (by IP address) to repeatedly perform TCP file transfers as rapidly as the network will allow until the test ends. These instructions, or scripts, are available for use in IxChariot so network administrators can simulate various types of traffic.

In tests with only a single AP under evaluation (Tests 1 and 2), we used the High Performance Throughput.scr, which continuously performs a 10 MB file transfer for the duration of the test. The test evaluating multiple APs (Test 3) utilized the Throughput.scr, which transfers a 1 MB file for the test's length. All IxChariot tests were run in 'batch' mode for 2 minutes. All tests included runs with traffic downstream (from AP to client), upstream (from client to AP), and bi-directional (both directions simultaneously):

- For single client testing (Test 1), 6 Chariot pairs (TCP streams) were used per client in both downstream and upstream runs. For bi-directional traffic, we used only 5 Chariot pairs: 4 downstream, 1 upstream.[16]
- For multi-client testing (Tests 2 and 3), only 1 Chariot pair was used per client. In bi-directional tests, every fifth client was instructed to do an uplink. This allowed us to achieve our desired traffic asymmetry in a somewhat simpler manner.

All clients communicated with a single IxChariot Console, which acted as the second endpoint in all our tests. The computer was validated to be able to accommodate over 800 Mbps in traffic and would not be a bottleneck for test purposes.

General Access Point Configuration

Except as given in this section or as described in the individual test explanation, the system defaults were left alone.

- Tests in the 2.4 GHz band used 20 MHz channels, while tests in the 5 GHz band used 40 MHz channels.
- Two open, unencrypted SSIDs were used in each test, one for each frequency band.
- AP channel selection was static in our single AP tests (Tests 1 and 2)— channel 1 at 2.4 GHz and channels 36 + 40 at 5 GHz— but was dynamically assigned in our multi-AP test (Test 3). The assignment was done by each vendor's channel selection

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[14] IxChariot Console version 6.70, build level 44 (retail). Chariot endpoint version: 6.70.27.32

[15] IxChariot Console was installed on a Dell Latitude 6220, Windows 7, SP1

[16] This bi-directional ratio of pairs was decided upon because it mimics traffic patterns experienced on Syracuse University's campus WLAN.

algorithm. After one hour of operation, the algorithm's dynamic assignment was statically configured. See Figure 6 below for channel assignment in Test 3.

- All vendors operate with 400 nanosecond guard intervals by default except for Aerohive[17].
- The access point was mounted at ceiling height, though placement of the AP is specific to each test. For AP location information, see the individual floor map for each test.

Test 1 - Single AP, Single Client (rate vs. range)

In some ways, our first test was similar to what many organizations do when they are evaluating different vendor's access points: they use a single AP and a single client and test throughput at various locations. However, we added several important variables to this simple test. In addition to testing both frequency bands individually, we tested them simultaneously— which, by nature, requires two clients. Hence, we tested a single AP, with a single client per frequency band. Clients were identical MacBook Pros placed on tables about 3 feet apart from one another. Both clients were associated for all tests, each on its designated SSID/channel. We chose to use MacBooks for these tests because they provided slightly higher throughput than we were able to achieve with our Dell/Intel notebooks.

We tested at five locations of various distances and RF "difficulty." At each location, we tested the throughput of directional traffic (downstream, upstream, and bi-directional), tested them in both frequency bands (including, as mentioned above, in both bands simultaneously[18]) and also introduced orientation variation. As the specific position and placement of a client will typically render different results, we ran tests with three different orientations. The first test had the client's screen opened to a comfortable viewing angle (approximately 70º), oriented 'facing' the AP, so to speak. Next, the client was rotated 45º clockwise from the original orientation, then finally set 45º counter-clockwise from the original orientation. Reported results are the average of these 3 test runs[19]. Each test run was 2 minutes long. Thus, after averaging, we have 45 comparisons across 5 vendors[20].

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[17] This was not caught until after Aerohive's Test 1 data was obtained under 800 nanosecond guard intervals. All Test 2 and 3 data used 400 nanosecond guard intervals.

[18] The terms "simultaneous" and "bi-directional" can be somewhat confusing. Here, we use the term "simultaneous" to refer to tests of both 2.4 and 5 GHz at the same time. "Bi-directional" tests are concurrent tests of traffic headed downstream and upstream from the access point.

[19] Client orientation is more or less an unpredictable variable in WLANs. By introducing different orientations and then averaging them, we attempted to capture how different vendors respond to that randomness.

[20] It took 135 test runs to complete each vendor, meaning that it took 675 IxChariot runs to complete Test 1 (a period of approximately 22.5 hours).

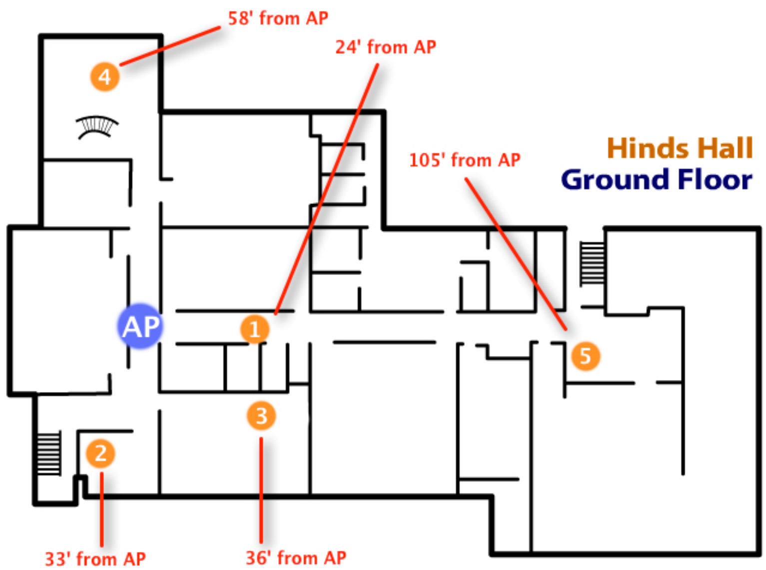

Figure 1: Floor plan of Hinds Hall with locations of Test 1 APs

A description of our five locations follows, ordered from shortest to longest distance from the access point:

1. Hallway, 24', line of sight (LOS) from the AP. Location where we expected the highest aggregate throughput.
2. Study lounge, 33'. Room has a large opening for a door, but is otherwise glass-enclosed.
3. Classroom, 36'. In a straight line from the AP, there are 3 intervening walls (drywall).
4. Study hall, 58'. Clients are positioned around the corner from the AP.
5. Hallway, 105'. Our most difficult location, clients are positioned behind a wall but in the same hallway as the access point. Near-LOS.

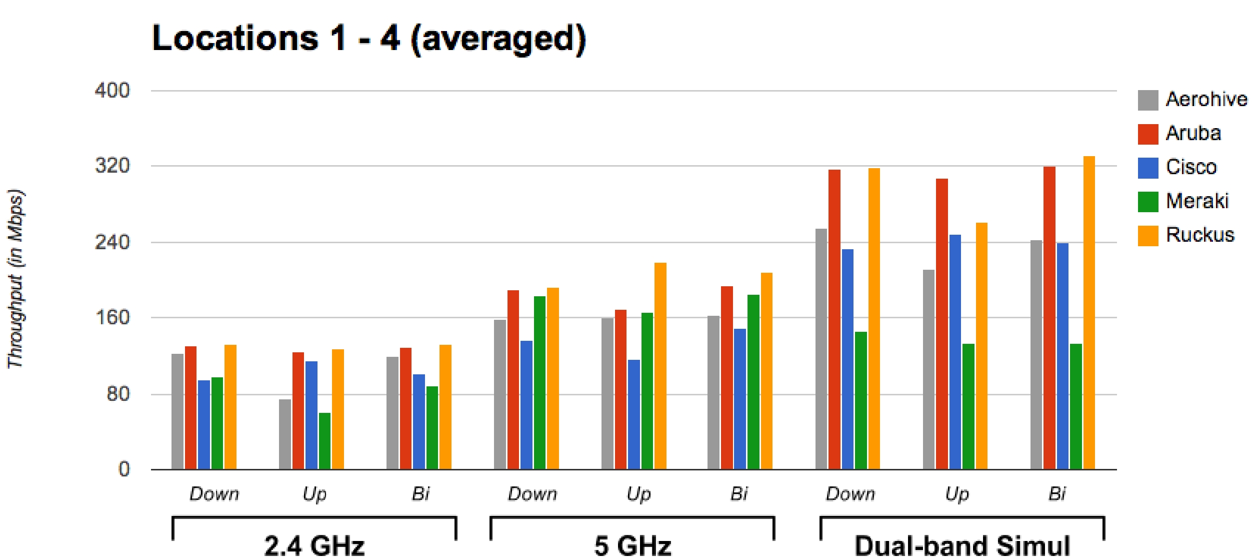

Figure 2: Average of locations 1 through 4

Figure 2[21] shows that most vendors' performance in a single client, single AP environment is generally similar. In these tests, results from the Aruba AP-135 and Ruckus ZoneFlex 7982 were particularly close. At location 1 (24') during the dual-band bi-directional test— the place we saw the highest aggregate throughput— Ruckus averaged 371.9 Mbps with Aruba close behind at 368.1 Mbps. Both results are impressive, but even in the best case, the throughput is only a little more than 55% of the maximum data rate of 666.7 Mbps.

Note that throughput at 5 GHz, where bandwidth is double what it is in 2.4 GHz, there is roughly a 75% boost over throughput at 2.4 GHz.

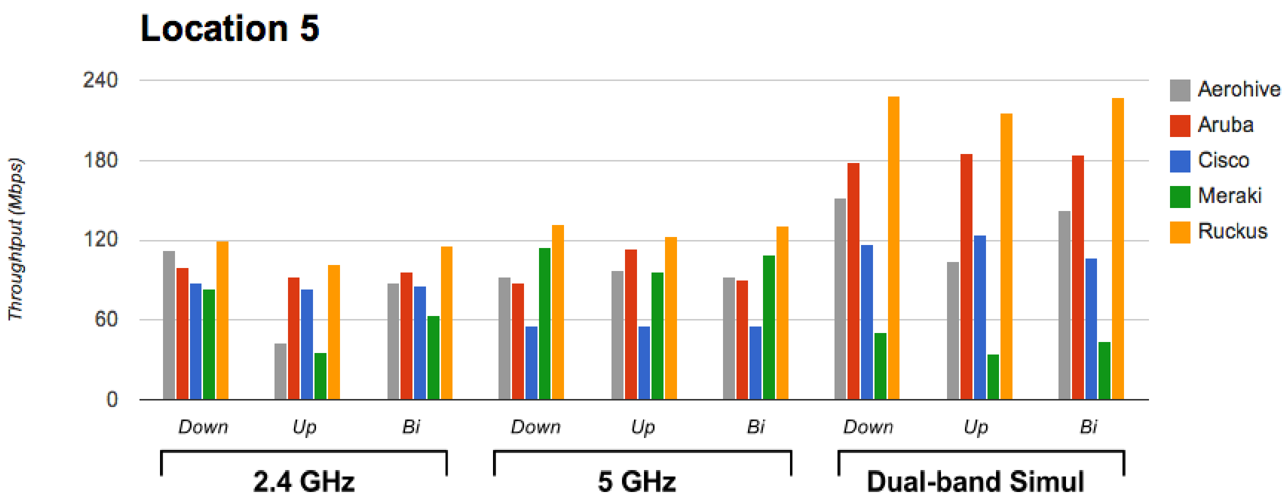

Figure 3: Location 5, 105 feet

Figure 3 shows the most distant location (105 feet) from the access point. This location is an example of what might be expected from the performance of a client at the edge of coverage.

The Ruckus AP again performed very well, achieving the highest aggregate throughput in each test at this range.

Of interest is the comparative performance between Meraki in each of the frequency bands. At 2.4 GHz, Meraki merited the lowest aggregate throughput in each run. At 5 GHz, though, Meraki had excellent throughput, even delivering the second-highest throughput in the down and bi-directional tests. In dual-band simultaneous, where all other vendors posted their respective bests (as would be anticipated; there are two clients in dual-band tests instead of one), Meraki

[21] In figure 1, we've averaged the results of locations 1 through 4. We've done so in view that the distances of the four locations are all within what is expected to be attainable of a single AP in a capacity-based deployment. Individual room results can be found in the appendix.

posted three of its four worst. This is a direct extension of its performance at 2.4 GHz[22].

Test 2: Multiple classrooms of simultaneous users on a single AP

Our second test was a high density evaluation of a single access point, measuring aggregate TCP throughput in a similar fashion to Test 1: down, up, and bi-directional. The access point was in the same place as it was in Test 1, but was accompanied by a total of 90 client devices. Three rooms of different distances to the AP were outfitted with 30 clients apiece. These clients, a mix of laptops and PCs with three-stream USB adapters, were divided across the spectrum in order to mimic an optimal arrangement of clients in each frequency band: 10 clients in each room were at 2.4 GHz, while the other 20 were at 5 GHz[23]. While physical arrangement of the PCs was not required (as they were already staged in a computer lab environment), the laptops were arranged in front of seats and opened as if facing a student. The room/client assignment was as follows (given room distances are measured from the central point in the room to the AP under test):

1. Room 1: 20’ from AP - 30 PCs with Netgear USB adapters
2. Room 2: 45’ from AP - 26 MacBook Pros and 4 Dell
3. Room 3: 55’ from AP - 30 PCs with Netgear USB adapters

Each room was evaluated three times by Chariot (2 minutes each run) before moving on to the next room[24]. Finally, all rooms were simultaneously tested, three times. Reported results are averages of the three iterations[25].

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[22] In the interest of full disclosure, we reached out to all vendors prior to conducting these tests and Meraki expressed a willingness to provide support if needed. We were concerned enough about the performance in our initial tests so we reached out to their technical staff. After viewing the results, they released to us a newer firmware release, which we used to re-run our tests. In general, results were substantially improved, and all reported results we’ve provided are from that version— with the exception of location 5 data. With the latest version, Chariot was unable to reach the clients at all for those long-distance tests. In order to provide some mode of comparison, though, we have decided to include location 5 results which were obtained under the initial software release (as Meraki publishes no version number, the test date will have to suffice. Initial Test 1 data was obtained on 1 August 2012 firmware. Meraki’s results for Test 2 were also obtained on this firmware.)

[23] Said another way, every third client device in a room was assigned to the 2.4 GHz band/SSID, the other two-thirds were at the 5 GHz band/SSID.

[24] All 90 clients were associated with the AP for the duration of the test, not just when they were in the room being tested. However, as the data show, not all access points could handle the load.

[25] With 3 directions of traffic (down, up, bi-directional), 4 classroom tests (room 1, 2, 3, then all rooms simultaneously), 3 iterations at 2 minutes each, and 5 vendors to test, we completed 180 Chariot runs, a period of 6 hours.

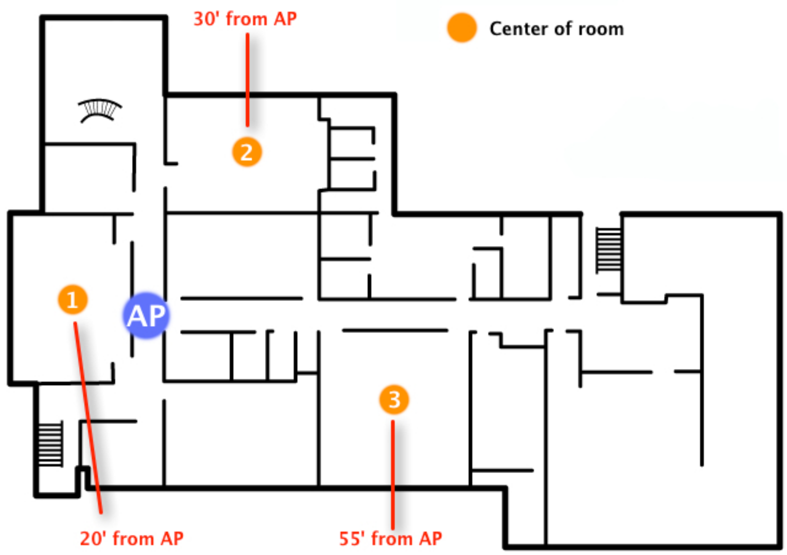

Figure 4: Floor plan of Hinds Hall with locations of Test 2 APs

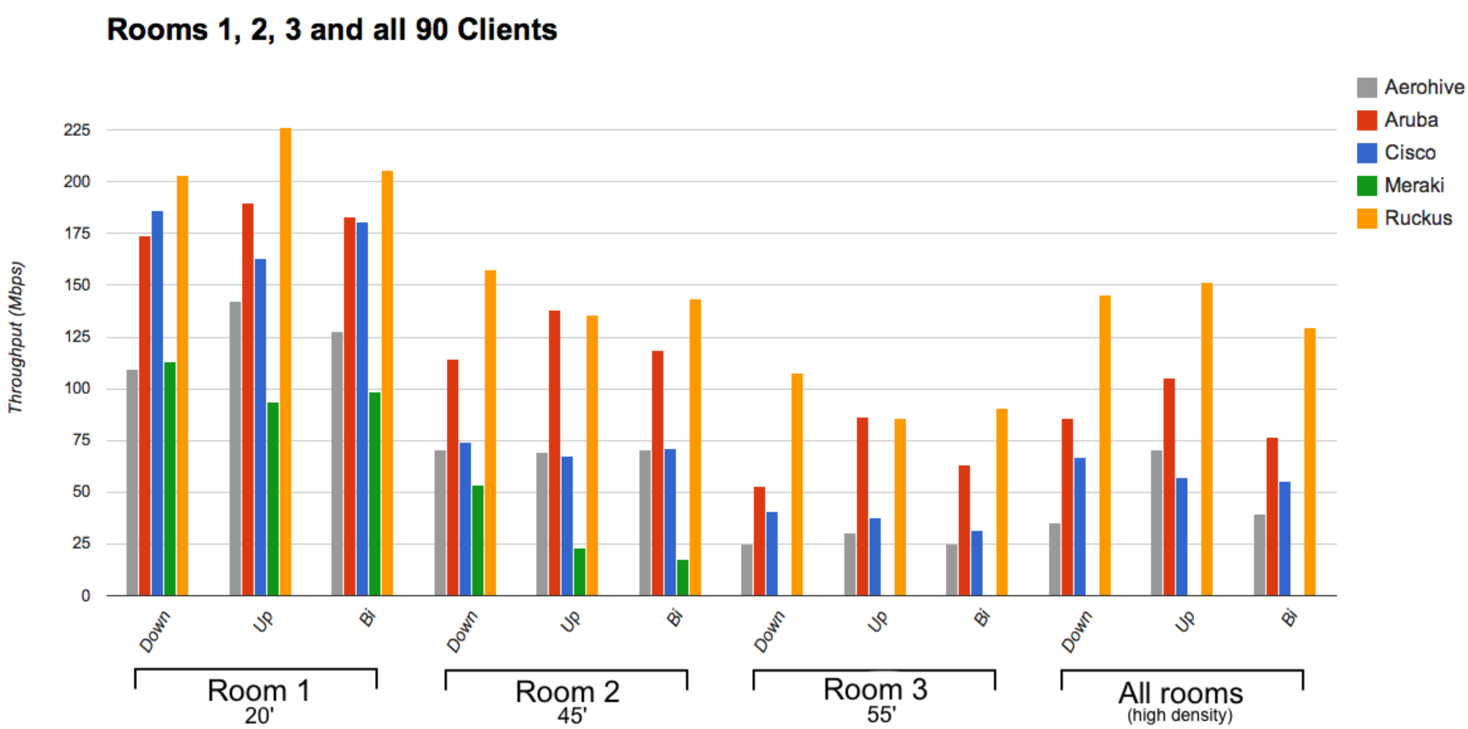

Figure 5: All rooms are presented individually, then all together

In case there was any doubt, figure 5 confirms that Wi-Fi performance degrades as distance increases. This, of course, holds true across all vendors' products but may be less noticeable depending on vendor, as the bar set by some products is much higher than others.

Throughput was again highest for Ruckus and Aruba access points, with Aruba's AP-135 only edging past the ZoneFlex 7982 twice across the twelve test scenarios. At high density, Ruckus supported 90 clients in three different rooms at nearly the same rates in which it supported 30 clients in one room. With all rooms under test, Ruckus only fell off its Room 2 rates at most 13 Mbps— and even improved by 15 Mbps on its upstream performance. In the high density test, no vendor came within 46 Mbps of the ZF 7982.

Supporting 90 clients is certainly a chore, but supporting 30 at a fair distance is no easy task, either. Meraki's MR24[26] faltered completely at our distance location and in the all-room high density test, and delivered the lowest aggregate throughput in all but one run.

Throughput tells only part of the story in this test. Because the number of devices on a single access point is so high, the client failure rate[27] is an important metric to carefully evaluate. When clients fail in a test, throughput is shared between *fewer* clients, potentially raising the aggregate throughput. Figure 6 shows the aggregate throughput across vendors and their client failure rate. Rates shown are the average of three runs.

	Room 1 - 20'			Room 2 - 45'			Room 3 - 55'			All rooms simultaneously		
	Down	*Up*	*Bi*	*Down*	*Up*	*Bi*	*Down*	*Up*	*Bi*	*Down*	*Up*	*Bi*
Aerohive	109.7	142.4	128.0	70.3	69.3	70.6	25.0	30.3	25.0	35.5	70.6	39.4
Client Failures	-	-	-	-	-	-	3	12.7	4	4.3	34.3	6.3
Aruba	173.8	189.9	182.8	114.4	**138.2**	118.9	53.2	**86.2**	63.4	85.5	105.3	76.6
Client Failures	-	-	-	-	1.3	0.7	10	15.7	11.3	34.3	6.7	18
Cisco	186.0	163.0	180.4	74.5	67.5	71.4	40.6	37.7	31.5	67.2	57.2	55.1
Client Failures	-	-	-	-	-	-	9.3	7.7	7	7.7	9	8.5
Meraki	113.0	94.0	98.8	53.4	22.8	17.8	0	0	0	0	0	0
Client Failures	-	-	-	-	13	5.3	30	30	30	90	90	90
Ruckus	**202.9**	**226.5**	**205.9**	**157.4**	135.6	**143.4**	**107.9**	85.9	**90.8**	**145.1**	**151.3**	**129.7**
Client Failures	-	-	-	-	-	-	10	2	2	2.33	4.33	2.67

Figure 6: Aggregate throughput with client failure metrics. Colored cells notate highest throughput.

It is interesting to note that in both instances where Aruba achieved the highest throughput, they had more client failures than their nearest competitor, Ruckus.

[26] Test 2 was completed before Test 1; the software version of Meraki's Cloud Controller is the version for which results are given in Figure 1.
[27] Either the client failed to set up on IxChariot and ran no traffic at all, or the client errored out in the middle of the test.

If we add the average client failures by vendor, we find Ruckus with the lowest amount (23.3 failures), followed by Cisco (49.2), Aerohive (64.7), and Aruba (98.0), and Meraki (378.3)[28]. Meraki's difficulties are summarized clearly by that last figure.

Test 3: Multiple classrooms of simultaneous users using multiple APs

Our third test was our most ambitious: 120 clients simultaneously across four classrooms. We began with the same three rooms from Test 2 and added an additional classroom. In each of these rooms, we installed an access point and placed two additional APs nearby our chosen locations in an attempt to force clients that could hear multiple access points to make strategic decisions. As both previous tests operated with only a single access point, there was no need before to be strategic about channel selection. In a test with six APs, however, channel assignment is important, particularly as 2.4 GHz has only three non-overlapping channels. AP channel assignment was determined by each vendor's channel selection algorithm, which we ran for one hour prior to throughput testing. When the hour had completed, the selected channels were fixed manually in order to prevent channel change during our test runs[29]. Client load balancing and airtime fairness were enabled at each vendor's respective point of control[30].

Like before, we tested throughput in downstream, upstream, and bi-directional[31] scenarios, though this time with five runs instead of three; reported results are an average of these five runs. One-third of the clients in a room were associated at 2.4 GHz with the rest at 5 GHz; on the whole, that means that 40 clients were associated to the lower band, while 80 were at the higher band. Client orientation (for non-laptop clients) was set to be "student-facing". All clients were associated for the test's duration. No attempt was made to ensure clients stayed on the in-room AP, as client load balancing was turned on at the APs. Room layout is as follows:

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[28] 378.3 out of 540 (9 runs with 30 clients each + 3 runs with 90 clients each). In other words, in Test 2, Meraki had a 70% failure rate. Aruba had a 18% failure rate, Aerohive had 12%, Cisco had 9%, and Ruckus led with only a 4% failure rate.

[29] We did not limit the vendors to the non-overlapping channels in the 2.4 GHz band, though they generally stayed there.

[30] *Client load balancing* is a feature which is conceptually similar to band steering. In band steering, the goal is to move clients off their current frequency band and on to the other. The goal of client load balancing is not to move a client to another band, but to an adjacent AP. This is often accomplished when fully "loaded" APs withhold probe responses to inquiring clients. *Airtime fairness* is a feature that makes time the primary metric of fairness instead of frame transmission. A client with a slower standard may send 2 frames per millisecond, while a faster one may send 6 frames per ms. A "frame round-robin" approach to fairness would likely lead to throughput inefficiencies.

[31] In Test 3 bi-directional scenarios, we instructed 24 clients to upload (8 on 2.4 and 16 on 5 GHz) while 96 clients downloaded (32 on 2.4 and 64 on 5 GHz).

1. Room 1: 30 PCs with Netgear USB adaptors
2. Room 2: 24 MacBooks, 6 Dell laptops
3. Room 3: 30 PCs with Linksys USB adaptors
4. Room 4: 30 PCs with Netgear USB adaptors

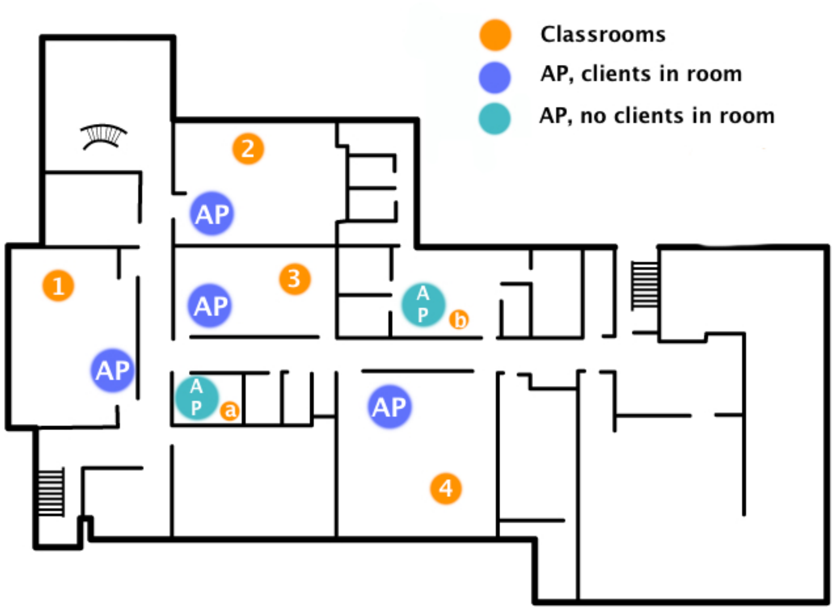
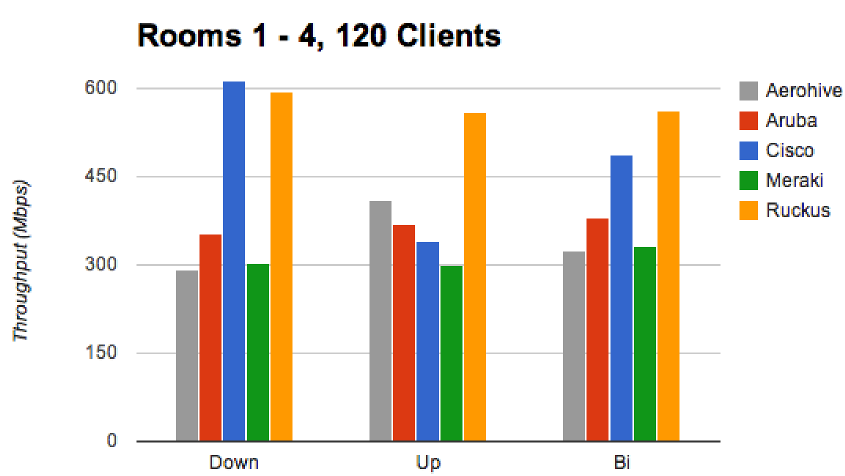


Figure 7: Floor plan of Hinds Hall with locations of Test 2 APs



	Down	*Up*	*Bi*
Aerohive	292.0	408.2	323.8
Aruba	354.4	369.6	378.8
Cisco	**617.6**	339.4	487.6
Meraki	303.1	299.1	330.4
Ruckus	592.7	**560.4**	**561.8**

Figure 8: 4 rooms simultaneously across 6 access points, average of 5 runs

With 6 access points, the highest theoretical aggregate data rate is approximately 4000 Mbps, or 4 Gbps[32]. Aggregate throughput might be about half that amount because of overhead, client contention, physical obstacles, and self- or other interference. Even with switching bottlenecks at 1 Gbps, reaching cumulative throughput of 600 Mbps across 120 clients is no small feat.

Cisco's 3602i achieves the highest throughput in our downstream tests, with an impressive 617.6 Mbps. Not far behind is Ruckus' ZF 7982 with 592.7 Mbps. With hardly a reduction from that rate the ZF 7982 easily performs at the highest throughput in the up and bi-directional tests. Throughput is not an orthogonal attribute; an AP's channel selection will have a measurable effect upon performance. After allowing channels to be selected over the course of an hour, we set and recorded the channels for each AP.

AP Channel Selection

	Aerohive		Aruba		Cisco		Meraki		Ruckus	
Room	2.4 GHz	5 GHz	2.4 GHz	5 GHz	2.4 GHz	5 GHz	2.4 GHz	5 GHz	2.4 GHz	5 GHz
1	6	36	1	157	11	44	6	36	1	36
2	6	149	6	153	1	52	1	36	11	165
3	11	157	6	149	6	60	11	149	1	149
4	1	149	5	157	5	157	1	149	5	48
A*	11	44	2	153	1	149	11	44	10	157
B*	6	157	3	153	1	36	6	157	3	40

Figure 9: Test 3 channel assignment. An asterisk on the room number indicates there were no clients physically in the same room.

At 2.4 GHz, there were only seven instances (out of thirty) where a channel other than 1, 6, or 11 was chosen, showing that vendors' selection algorithms generally stick to the common wisdom of selecting the non-overlapping channels. Two vendors who eschewed the 1-6-11 paradigm were Aruba and Ruckus. Both had three of their six APs assigned to something other than a non-overlapping channel, and both made interesting channel-to-room assignments. When laid atop our floor plan, it is apparent that all six of Aruba's APs chose channels that would have interfered with a directly adjacent access point. For example, AP 'A', assigned channel 2, would have caused interference with all five neighboring APs. Rooms 2 and 3, separated by a single wall, were both assigned channel 6; throughput was likely affected by the co-channel interference[33]. Ruckus choose similar channels, though perhaps assigned them to classrooms slightly better, particularly with AP 'A'. Ruckus actually advertises their selection

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[32] Assuming simultaneous dual-band, 20 MHz bandwidth at 2.4 GHz and 40 MHz at 5 GHz, with short 400 ns guard intervals) and three streams on both ends.

[33] Co-channel interference occurs when different stations operate in the same channel. Because of the shared frequency, they must cooperate in order to have successful transmissions. They can cooperate because, sharing the same channel, they can demodulate each other's traffic. Thus, while broadcasting on a non-overlapping channel is optimal, sharing the same channel is better than being on adjacent channels, as adjacent-channel transmissions are sensed only as noise to the AP.

of overlapping channels as a feature[34], and their throughput results are telling. The difference in aggregate throughput between the two— even with somewhat similar channel plans— is interesting to note. So too is the performance difference between these two vendors and Aerohive and Meraki, which both assigned only non-overlapping channels in a more traditional cell layout[35].

Channel selection at 5 GHz is complicated. The higher WLAN frequencies are divided into several segments called the Unlicensed National Information Infrastructure (UNII) bands. While there are 23 channels defined here, comporting with the IEEE 802.11-2012 standard, only 20 of them are currently authorized for use in the United States. Of those 20, only 9 can be used *unless* an AP performs an additional radio function called dynamic frequency selection (DFS). Because the 5 GHz spectrum used by 802.11 stations shares some of the same frequencies as weather and military radar, a capable access point hoping to utilize those additional channels must first attempt to detect radar. If it detects (or thinks it detects) radar, the AP may not use those channels. These channels, the UNNI-2 and UNNI-2 Extended bands, grant a WLAN an additional 355 MHz of bandwidth. The IEEE standard, 802.11h, defined how devices could support DFS, yet many end-user devices have remained without the capability, and hence most vendors have default-disabled these channels from being assigned to their access points. And that largely makes sense: if an AP is on one of the DFS-required channels and the client doesn't support DFS, the client won't be able to connect to that AP at all. Therefore, even though the UNII-2 and UNII-2 Extended channels are available, many network administrators do not enable them.

In the United States, all 5 GHz channels which are regulatorily allowable are non-overlapping, at least when using channel widths of 20 MHz. But in 802.11n, which allows for channel bonding, many 5 GHz networks combine two 20 MHz channels to effectively double their data rates. Under the current practice of not enabling the UNII-2 and Extended bands, this leaves only 9 non-overlapping 20 MHz channels to be used— or, stated another way, this leaves only 4 non-overlapping 40 MHz channels to be used. At that point, channel reuse becomes as important to carefully manage in the higher Wi-Fi band as it does in the lower band.

Like our previous tests, Test 3 operated using 40 MHz-wide channels at 5 GHz. All clients we used could support all lawful UNII 5 GHz channels. But only one vendor took advantage of this fact, and that was our throughput leader in Test 3, Cisco. In rooms 2 and 3, their controller assigned channels 52 and 60, respectively— both UNII 2 channels. After investigating further, we realized Cisco was the only vendor in our test who by default allows the UNII-2 channels to be assigned by their channel selection algorithm. This fact certainly give the 3602i's an advantage, as instead of only four non-overlapping 40 MHz channels to work with they have (and use) six. Aside from a few crucial configuration options, our general theme was to leave controller defaults be. This is one aspect that, in the future, our team would be interested in standardizing across all products, should client stations allow it. We are hopeful that as support

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[34] ChannelFly is a Ruckus-invented technology which statistically analyzes the channel set over time and assigns channels based on potential for highest throughput.

[35] Obviously, however, there is more to performance than simply channel selection.

for 802.11h becomes standard, practitioners will enable the additional UNII channels and vendors will enable these channels by default[36].

Summary

The massive influx of Wi-Fi devices in the marketplace will continue to make their way onto the enterprise WLAN, presenting new opportunities and challenges for implementers. Although network capacity is only one of many considerations that must be carefully evaluated when making deployment decisions, it is one that will affect end-users directly. Our tests compared potential client performance in simple and difficult environments to demonstrate how different vendors handled the load. The results of our tests suggest that Ruckus Wireless' ZoneFlex 7982 is not only a reliably high-performing access point, but also a remarkably consistent one as well. It did not achieve the highest throughput in every test, but it did perform with general distinction across all our tests.

[36] Anecdotally, it appears that 802.11h is beginning to come standard with products that operate over 5 GHz. For instance, Apple has had 802.11h on all its 5 GHz products for the past three years, which includes the new iPhone 5 and iPad Mini.

Appendix

Vendor configuration files will be published on the CCENT website shortly after publication of this report.

Test 1 Throughput Data by Room

24', Location 1 - average of three orientations	2.4GHz			5GHz			Dual-band Simul		
	Down	*Up*	*Bi*	*Down*	*Up*	*Bi*	*Down*	*Up*	*Bi*
Aerohive	135.3	124.5	136.8	226.2	**230.7**	234.0	276.9	264.6	259.7
Aruba	136.2	134.4	136.4	234.9	220.7	227.3	361.1	**339.5**	368.1
Cisco	97.3	119.4	108.1	**243.0**	164.1	**268.8**	324.9	315.7	319.9
Meraki	93.5	66.8	91.2	228.6	193.8	222.3	199.3	175.3	192.4
Ruckus	**140.4**	**146.7**	**145.0**	213.0	224.5	241.1	**361.3**	271.0	**371.9**

30', Location 2 - average of three orientations	2.4GHz			5GHz			Dual-band Simul		
	Down	*Up*	*Bi*	*Down*	*Up*	*Bi*	*Down*	*Up*	*Bi*
Aerohive	133.4	64.3	131.2	189.9	168.8	193.4	290.3	244.9	287.0
Aruba	**145.9**	131.0	145.9	**215.6**	138.5	222.8	**359.8**	**335.2**	362.4
Cisco	108.7	125.6	114.4	157.0	126.5	166.5	251.1	294.9	263.5
Meraki	112.5	88.5	107.7	232.9	225.1	**237.0**	200.2	176.5	205.0
Ruckus	143.3	**137.2**	**146.5**	210.3	**249.4**	227.1	347.7	269.3	**364.5**

40', Location 3 - average of three orientations	2.4GHz			5GHz			Dual-band Simul		
	Down	*Up*	*Bi*	*Down*	*Up*	*Bi*	*Down*	*Up*	*Bi*
Aerohive	133.2	60.2	124.9	119.1	136.4	123.4	249.0	161.8	240.7
Aruba	140.3	**129.5**	136.4	157.8	140.8	168.0	283.0	**269.4**	280.7
Cisco	104.4	117.4	112.8	97.2	105.6	107.3	213.1	206.9	216.7
Meraki	104.3	69.4	94.2	**227.2**	205.2	**226.7**	113.3	110.3	96.3
Ruckus	**142.8**	125.4	**142.5**	194.7	**217.3**	202.0	**299.6**	255.0	**312.7**

58', Location 4 - average of three orientations	2.4GHz			5GHz			Dual-band Simul		
	Down	*Up*	*Bi*	*Down*	*Up*	*Bi*	*Down*	*Up*	*Bi*
Aerohive	92.0	52.2	83.6	101.3	102.7	100.3	202.0	173.3	183.6
Aruba	98.2	**104.5**	97.6	150.3	177.6	157.9	264.5	**290.6**	274.3
Cisco	67.4	99.9	70.6	50.7	69.5	56.6	143.7	180.4	159.1
Meraki	83.5	18.3	59.2	46.4	44.5	52.6	69.6	76.3	40.9
Ruckus	**100.3**	99.2	**97.8**	**157.0**	**185.2**	**162.5**	**268.3**	253.6	**274.6**

	2.4GHz			5GHz			Dual-band Simul		
Locations 1 - 4 averaged	*Down*	*Up*	*Bi*	*Down*	*Up*	*Bi*	*Down*	*Up*	*Bi*
Aerohive	123.5	75.3	119.1	159.1	159.7	162.8	254.6	211.2	242.8
Aruba	130.2	124.9	129.1	189.7	169.4	194.0	317.1	**308.7**	321.4
Cisco	94.5	115.6	101.5	137.0	116.4	149.8	233.2	249.5	239.8
Meraki	98.5	60.8	88.1	183.8	167.2	184.7	145.6	134.6	133.7
Ruckus	**131.7**	**127.1**	**133.0**	**193.8**	**219.1**	**208.2**	**319.2**	262.2	**330.9**

	2.4GHz			5GHz			Dual-band Simul		
105', Location 5 - average of three orientations	*Down*	*Up*	*Bi*	*Down*	*Up*	*Bi*	*Down*	*Up*	*Bi*
Aerohive	112.1	42.9	88.2	92.8	97.8	93.2	151.9	103.9	142.2
Aruba	99.6	92.3	96.6	87.8	114.1	90.0	178.8	185.5	184.1
Cisco	88.5	83.0	85.8	55.2	56.1	55.1	117.0	123.7	107.0
Meraki*	83.2	36.4	63.6	114.5	96.8	108.6	50.8	34.8	43.8
Ruckus	**119.6**	**102.4**	**116.2**	**132.7**	**123.2**	**130.8**	**228.2**	**215.3**	**227.8**

*Data from previous firmware. Latest firmware update yielded no results.